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SNOWMASS EF02  
HIGGS+FLAVOR MEETING  
SEPTEMBER 3, 2020

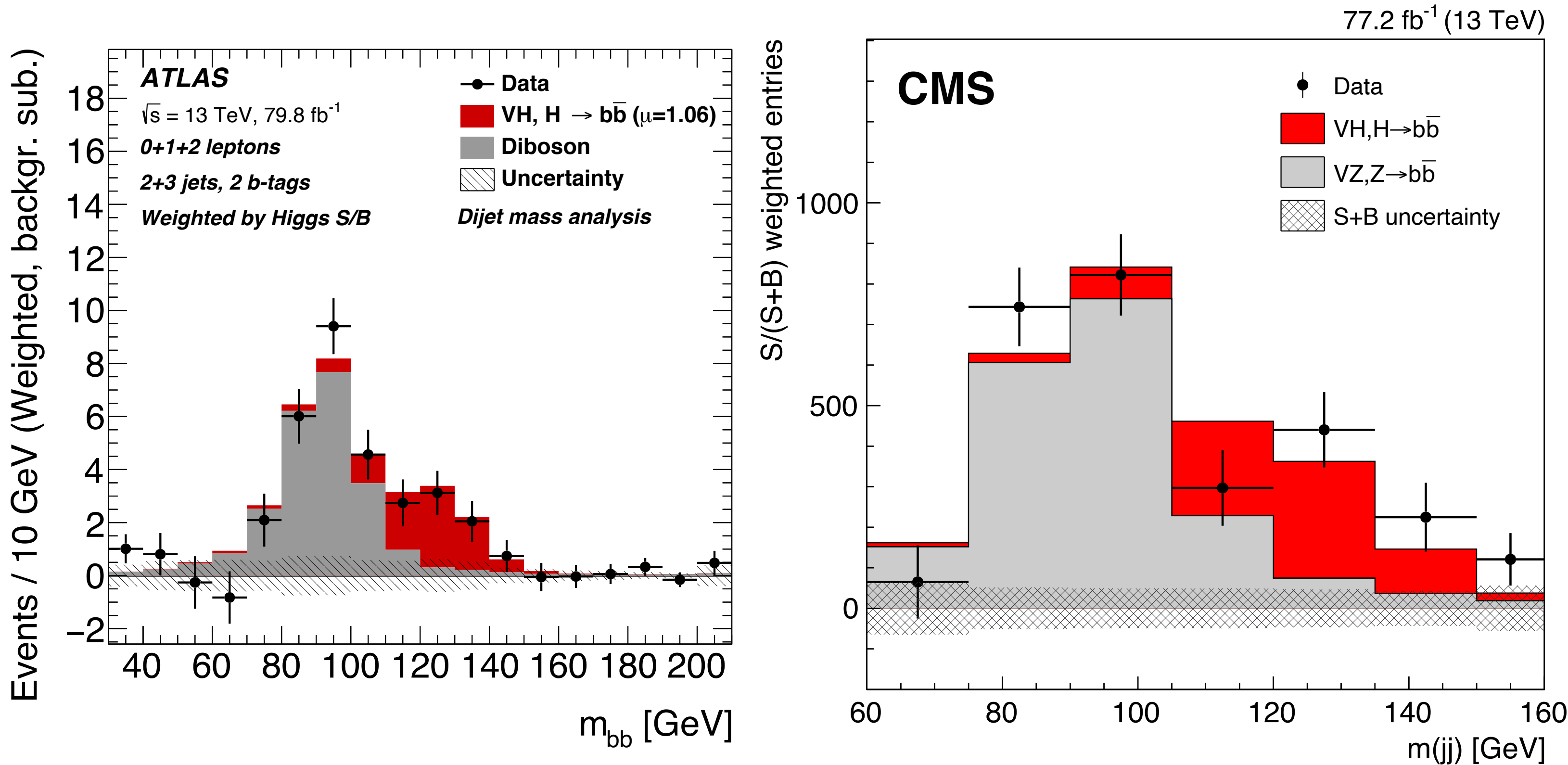
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# JET FLAVOR TAGGING FOR HIGGS PHYSICS

- ▶ Introduction
  - ▶ Overview of flavor tagging
  - ▶ Recent developments (ML)
  - ▶ Use in analysis
  - ▶ Experimental considerations
  - ▶ Use in the trigger
  - ▶ Summary and outlook
- 
- ▶ Note: Apologies for CMS-centric details

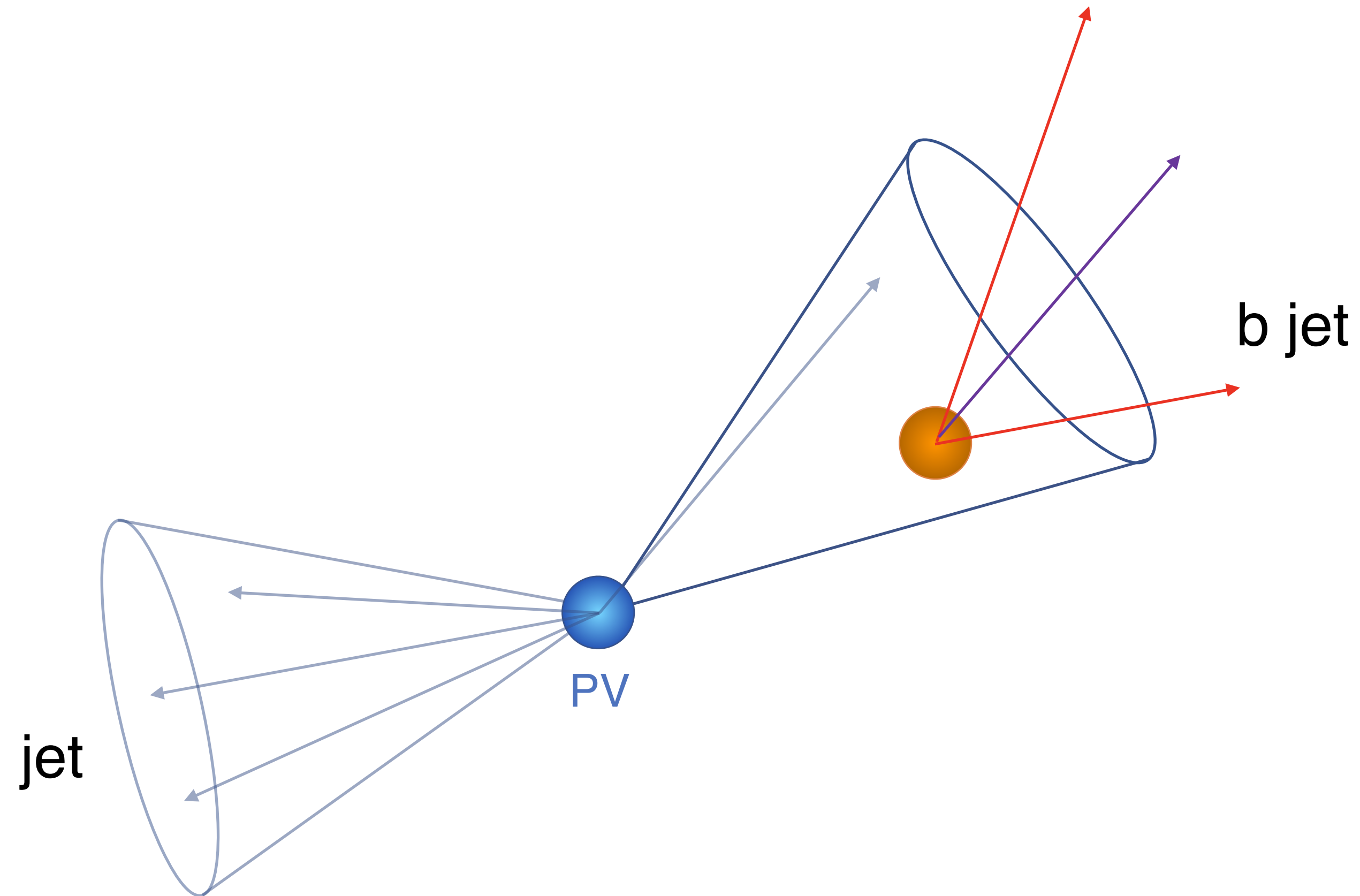
- ▶ Heavy flavor jet tagging is an important aspect of Higgs searches
  - ▶ Techniques have been “ML”-based for a while [[arXiv:1607.08633](#)]
    - ▶ e.g. in NN taggers in LEP [[arXiv:hep-ex/0311003](#)], D0 [[arXiv:1002.4224](#)], MV1 at ATLAS [[arXiv:1512.01094](#)] in ATLAS and cMVA, CSVv2 in CMS [[arXiv:1712.07158](#)]
- ▶ Recently played a role in the observation of VH(bb)
- ▶ Techniques are still evolving
- ▶ 2nd generation (charm) more challenging

H decay	BF
bb	58.2%
cc	2.9%



# HEAVY FLAVOR TAGGING APPROACHES

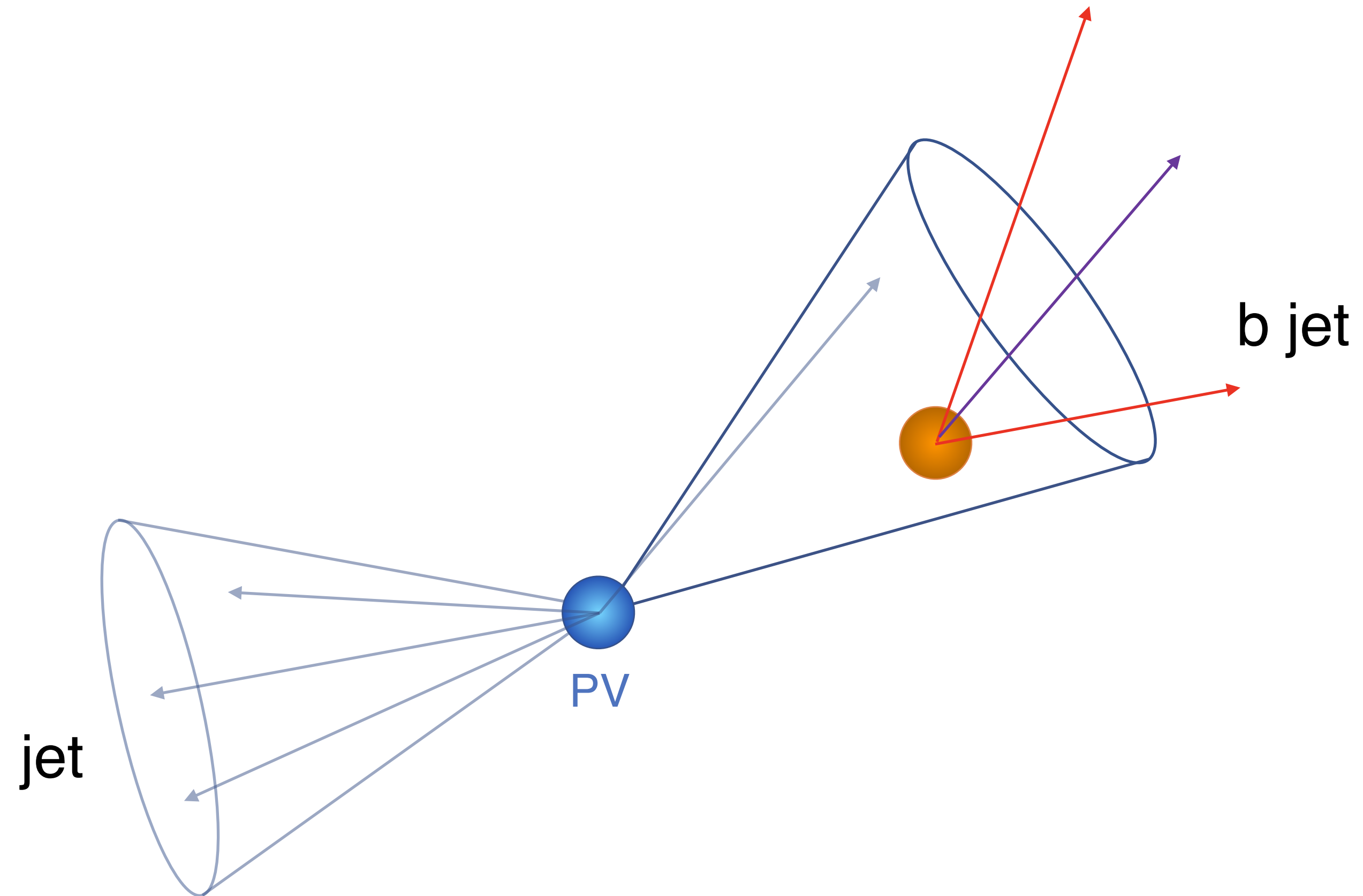
anti- $k_T$   
 $R=0.4$



# HEAVY FLAVOR TAGGING APPROACHES

► Handles:

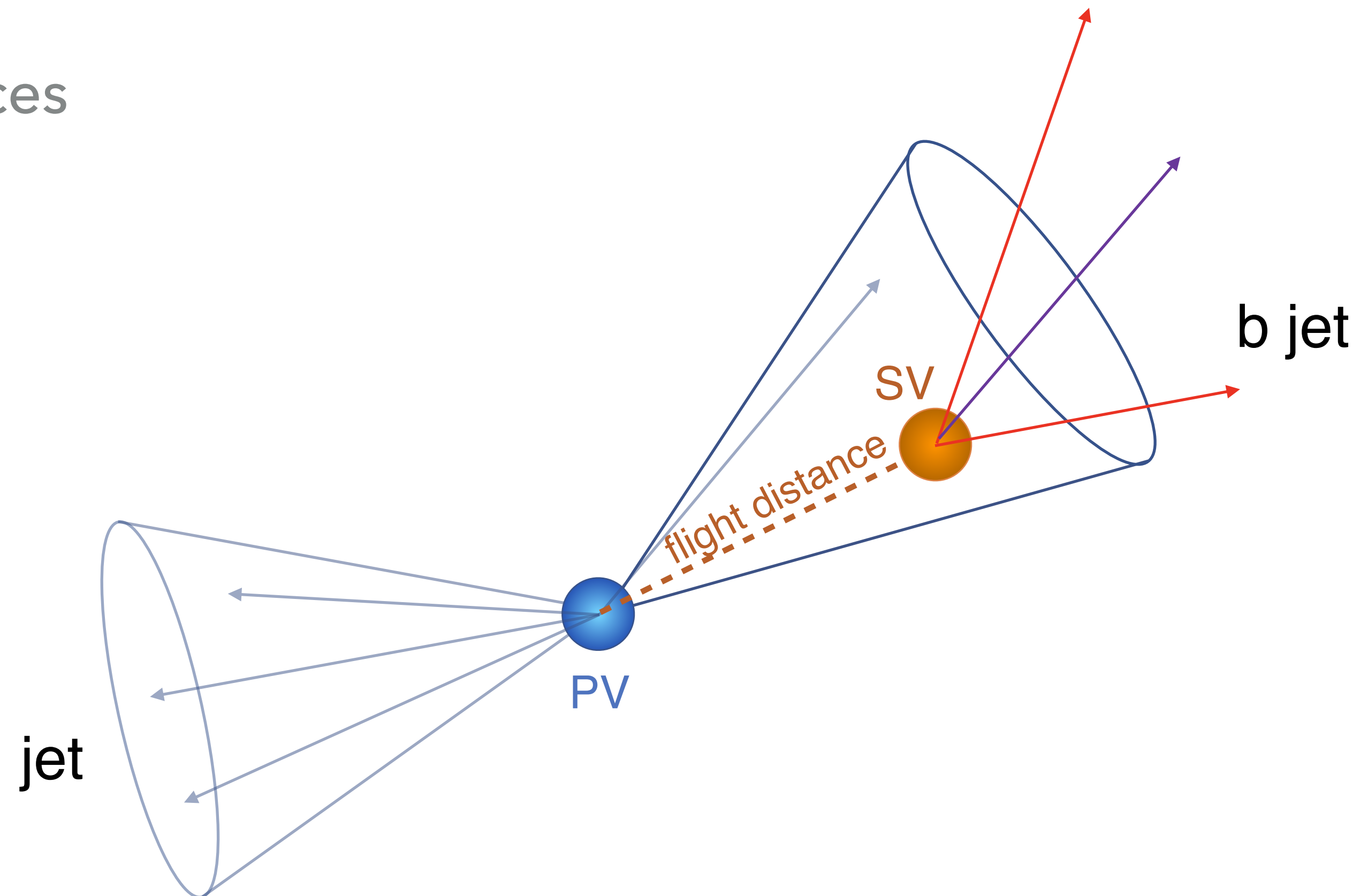
anti- $k_T$   
 $R=0.4$



# HEAVY FLAVOR TAGGING APPROACHES

- ▶ Handles:
  - ▶ secondary vertices

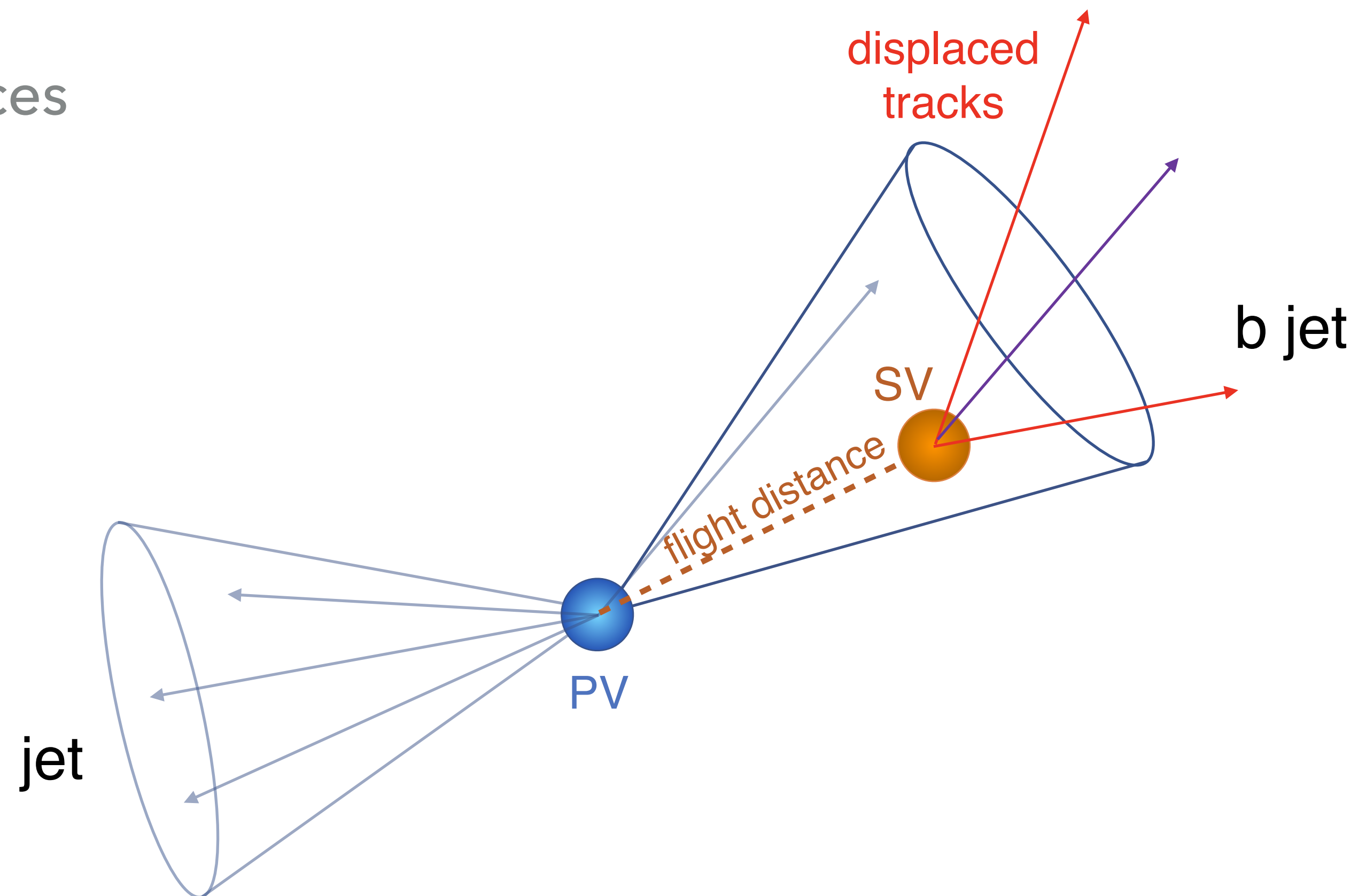
anti- $k_T$   
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# HEAVY FLAVOR TAGGING APPROACHES

- ▶ Handles:
  - ▶ secondary vertices
  - ▶ displaced tracks

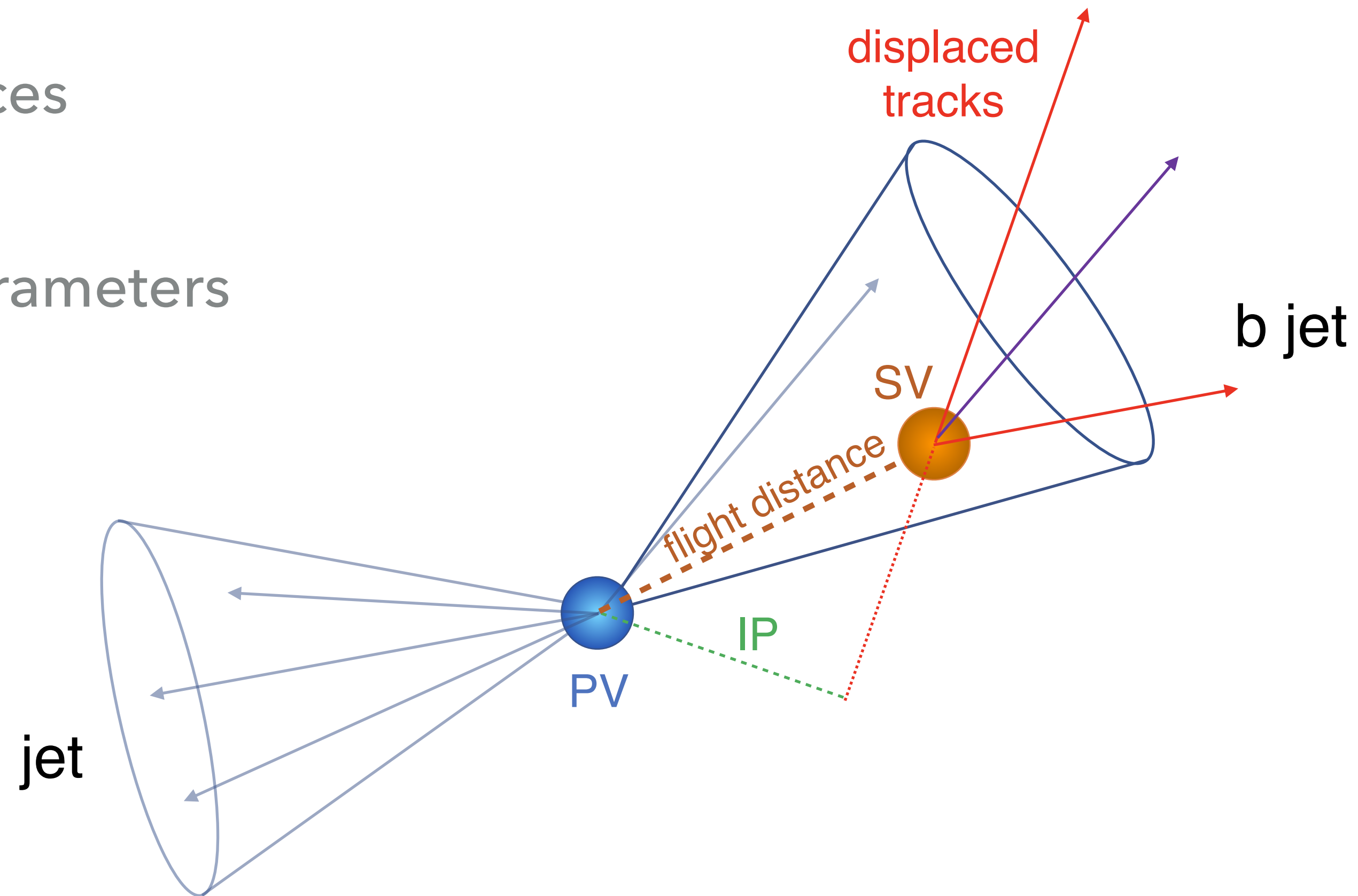
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# HEAVY FLAVOR TAGGING APPROACHES

- ▶ Handles:
  - ▶ secondary vertices
  - ▶ displaced tracks
  - ▶ large impact parameters

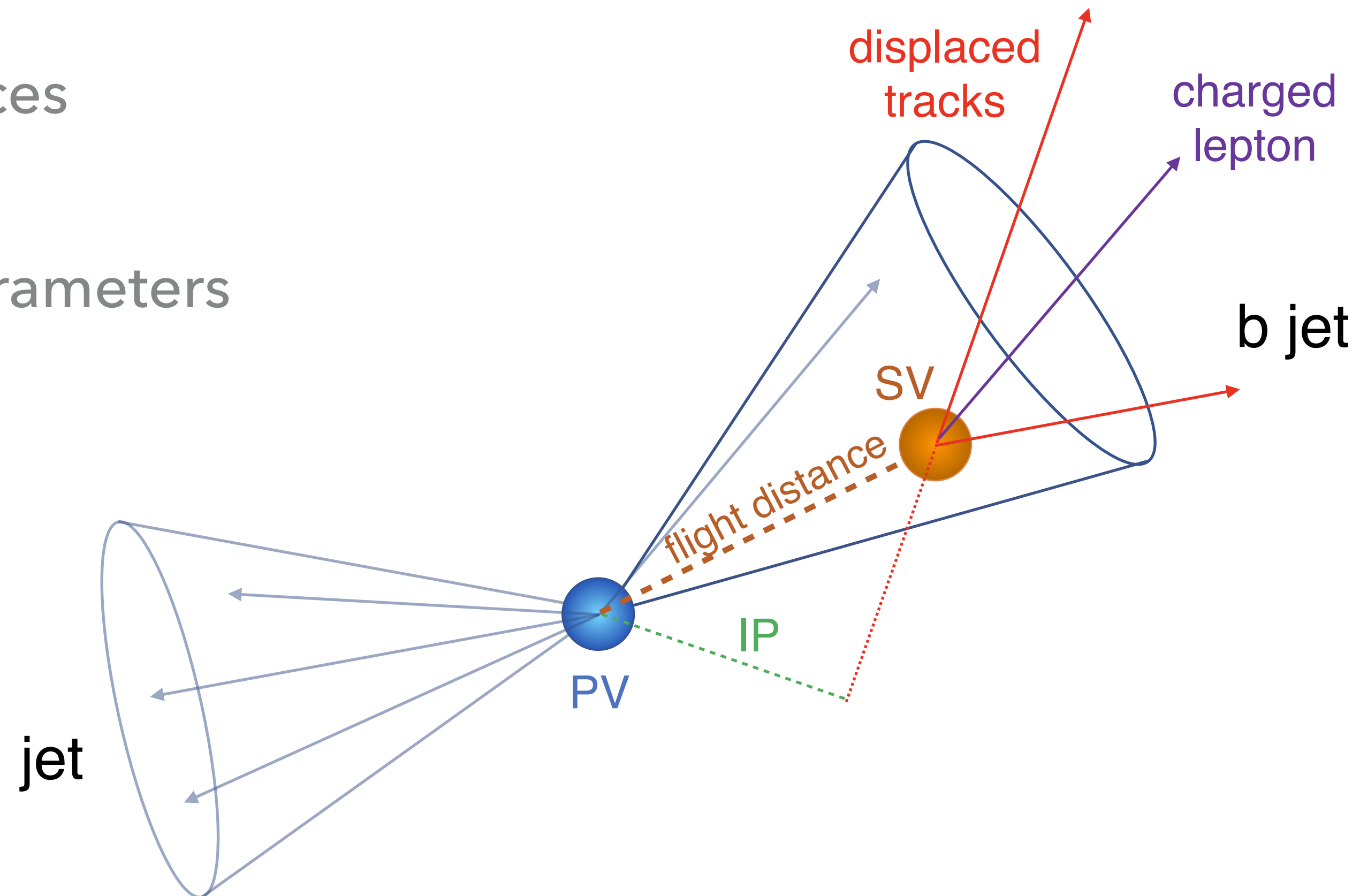
anti- $k_T$   
 $R=0.4$



# HEAVY FLAVOR TAGGING APPROACHES

- ▶ Handles:
  - ▶ secondary vertices
  - ▶ displaced tracks
  - ▶ large impact parameters
  - ▶ soft leptons

anti- $k_T$   
 $R=0.4$

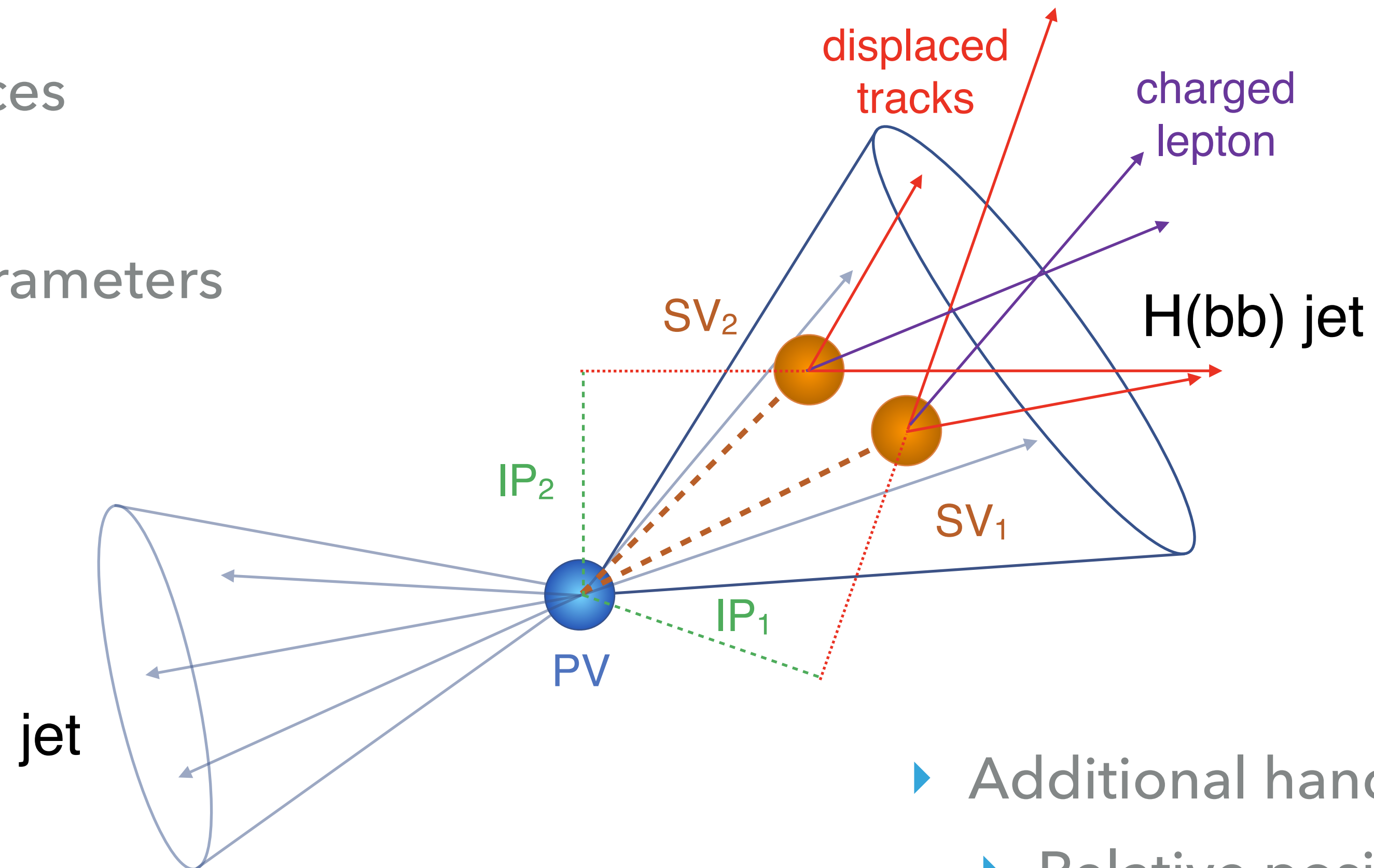


# HIGGS (DOUBLE-B) TAGGING

- ▶ Handles:

- ▶ secondary vertices
- ▶ displaced tracks
- ▶ large impact parameters
- ▶ soft leptons

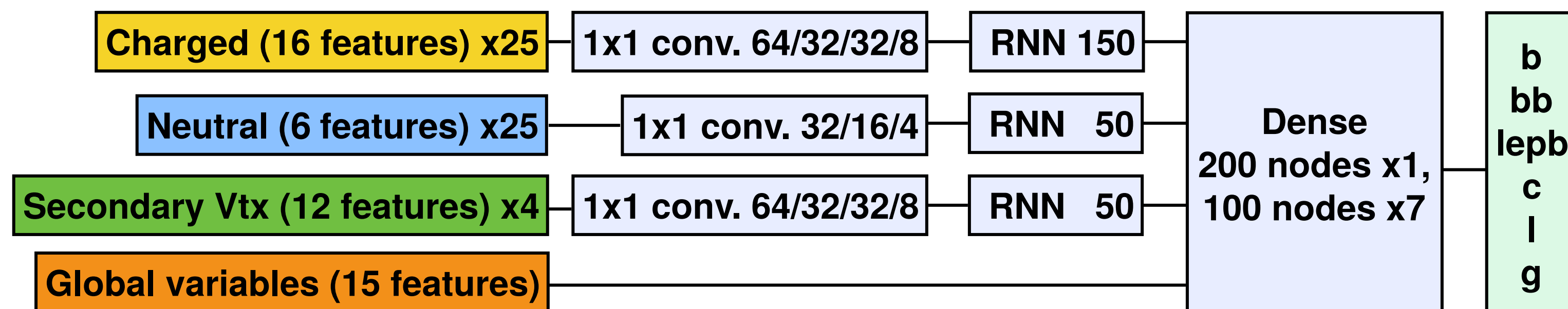
anti- $k_T$   
 $R=0.8$



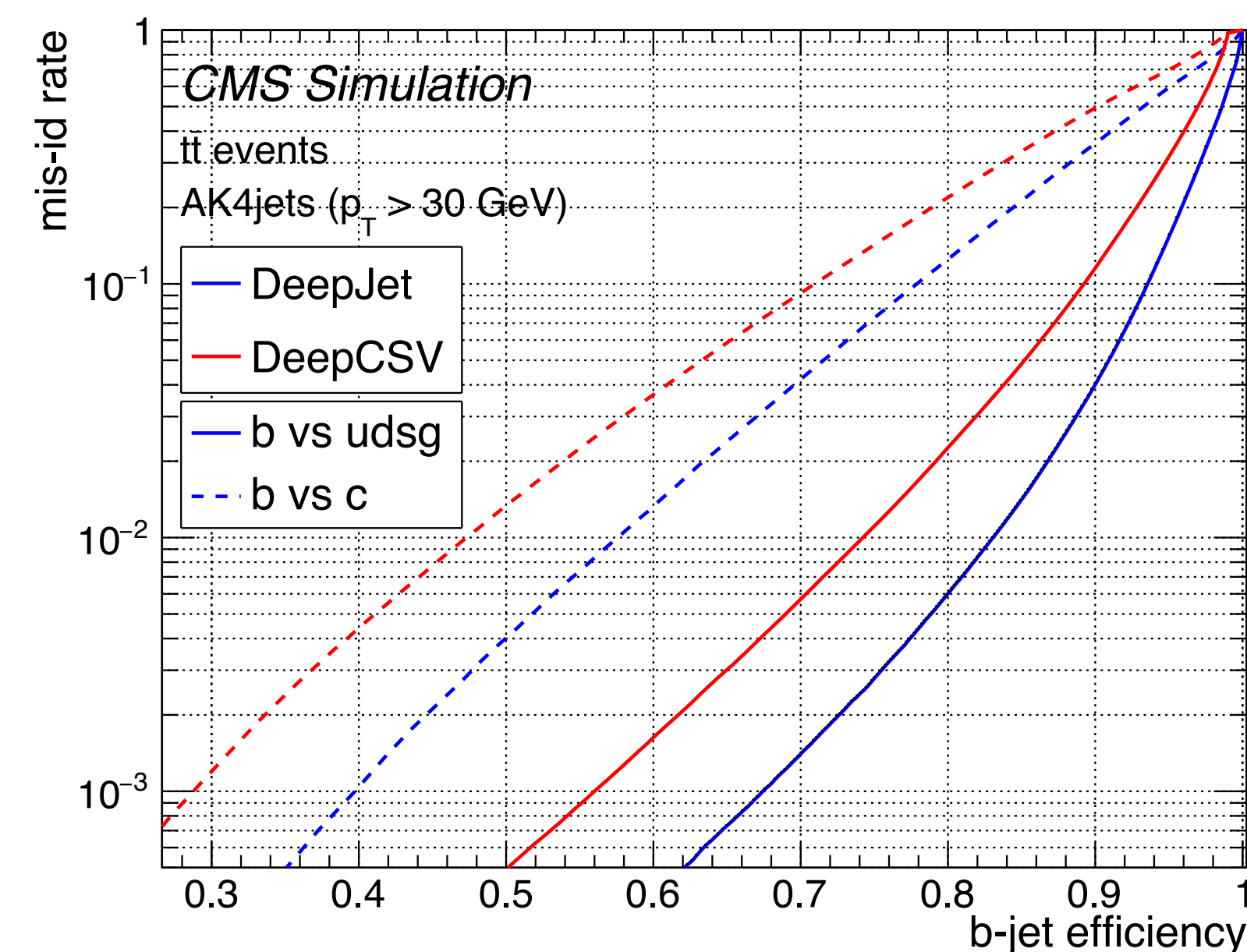
- ▶ Additional handles:

- ▶ Relative position of SVs

- ▶ DeepJet [[dlps\\_2017\\_10](#), [CMS-DP-2018-058](#)] considers low-level charged and neutral particle, secondary vertex, and global features to categorize the flavor of AK4 jets using a mixture of recurrent and dense neural networks



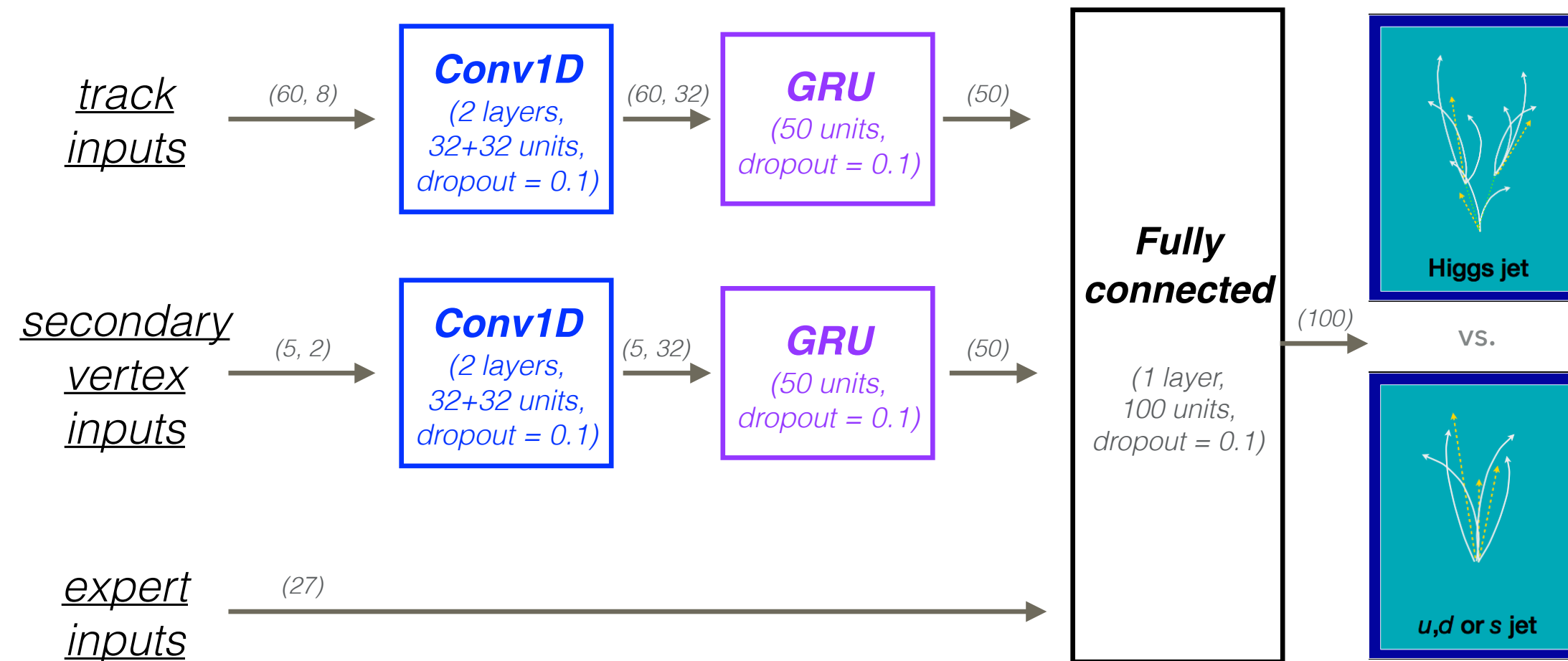
- ▶ Large improvement over previous methods:
  - ▶ DeepJet: 84% b-jet efficiency for 1% mis-id
  - ▶ DeepCSV: 75% b-jet efficiency



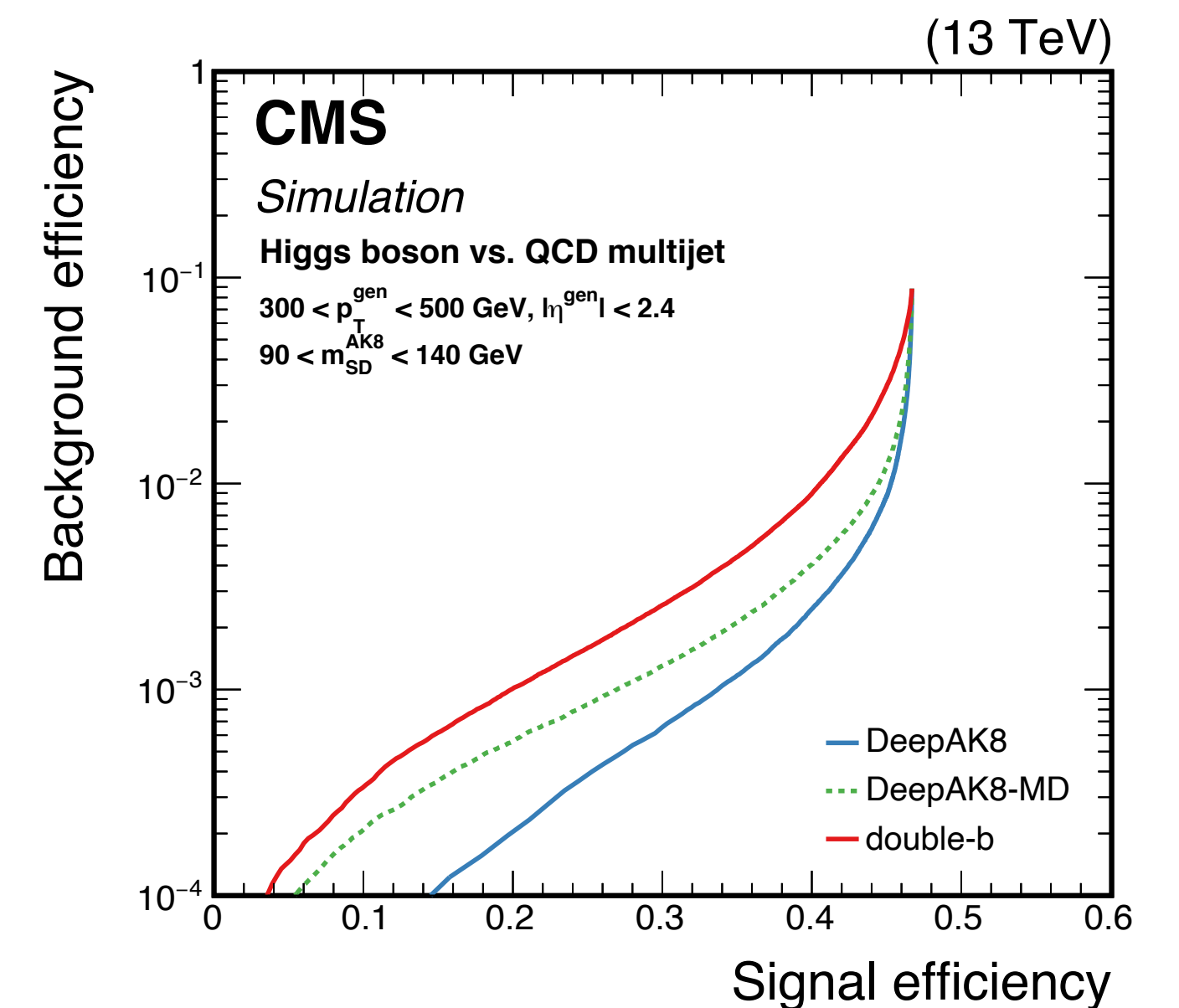
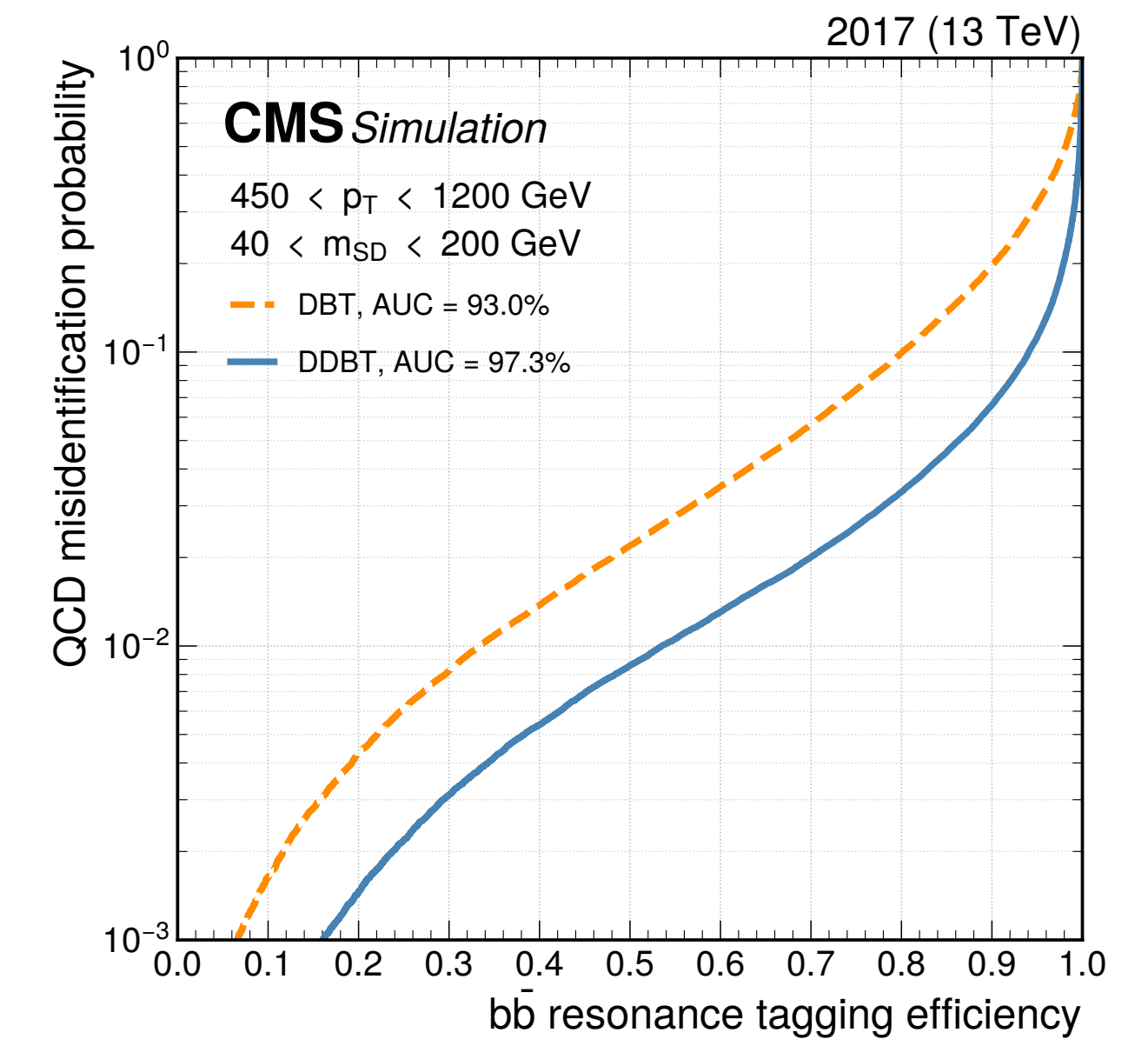
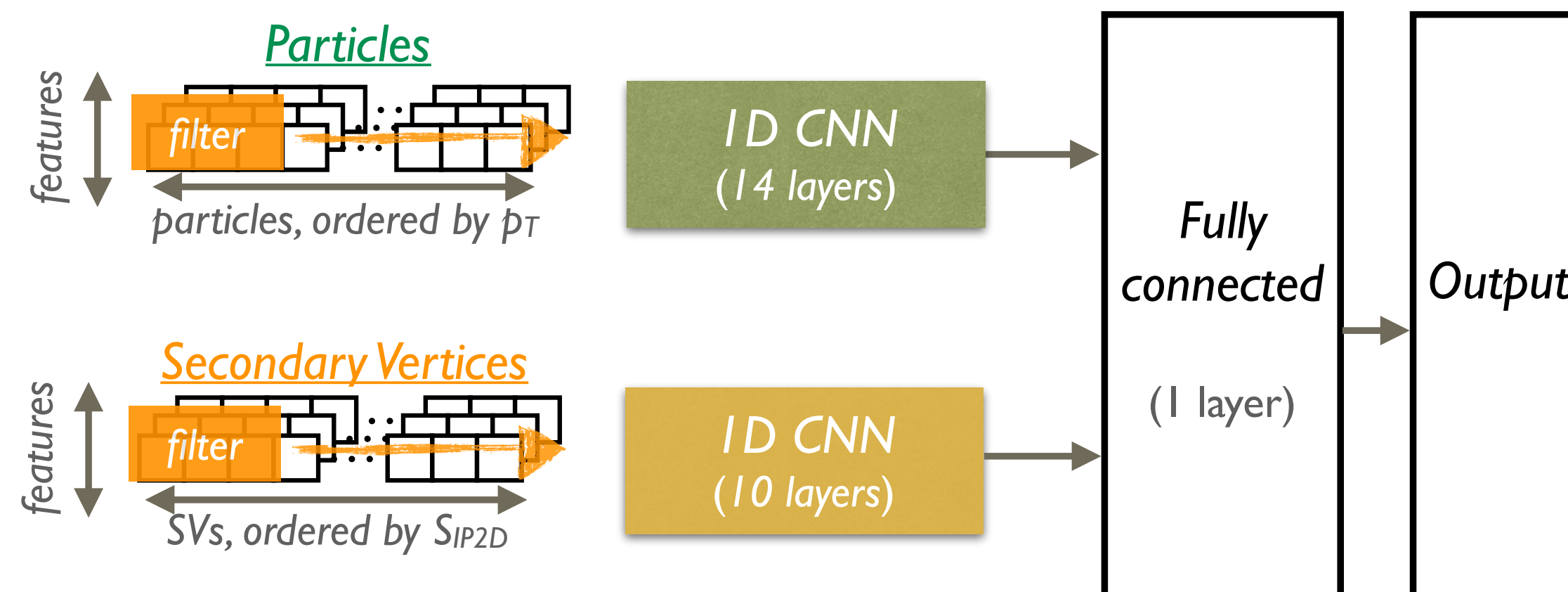
# DEEP DOUBLE-X, DEEP AK8 TAGGERS

- Deep double-x and deep AK8 in CMS: similar approach using low-level features now applied to large-radius jets
  - 50-70% H(bb) efficiency for 1% mis-id (depending on  $m_{SD}$ ,  $p_T$  range)
- Related: Higgs jet tagger in ATLAS [[arXiv:1906.11005](https://arxiv.org/abs/1906.11005)]

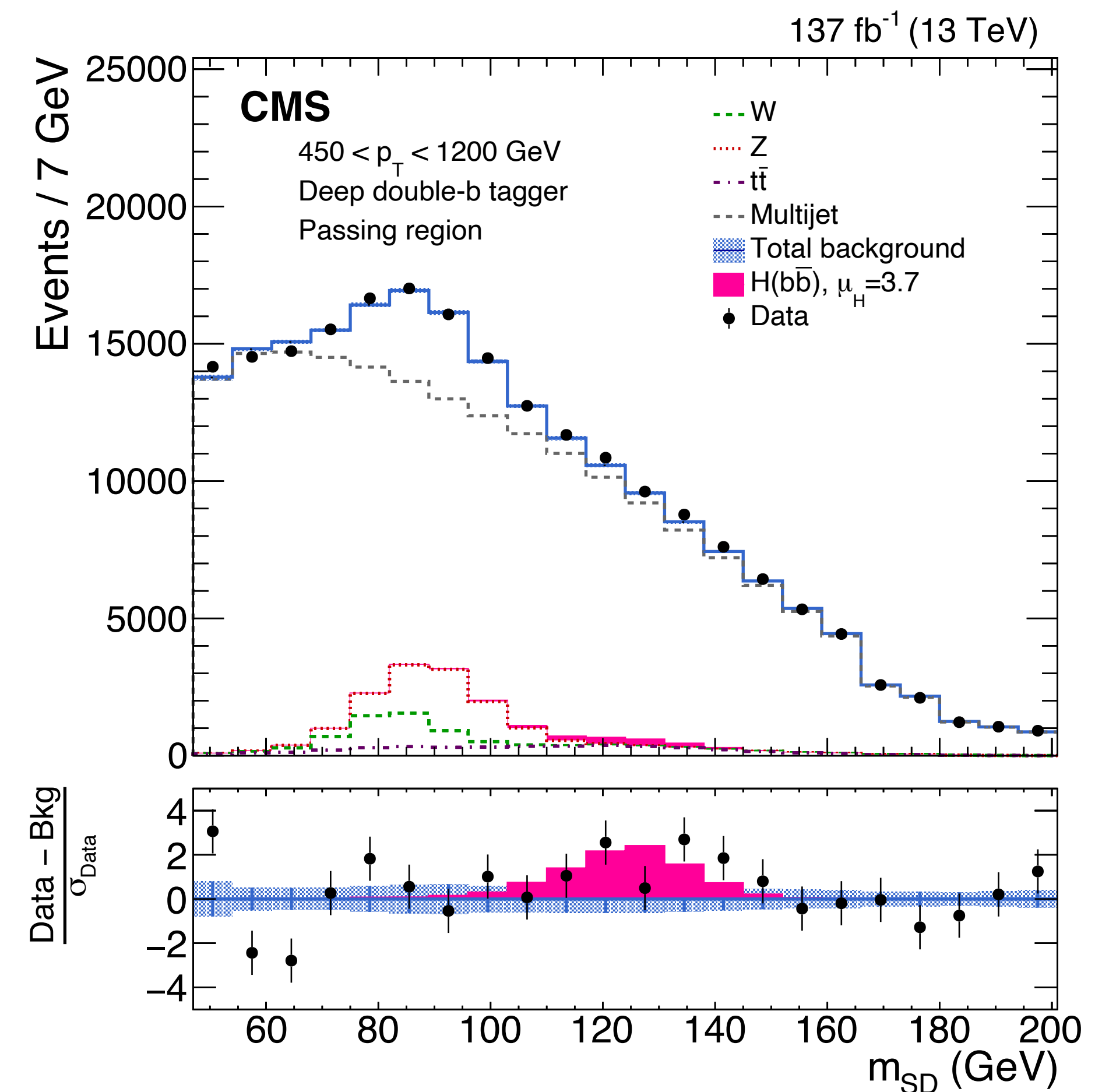
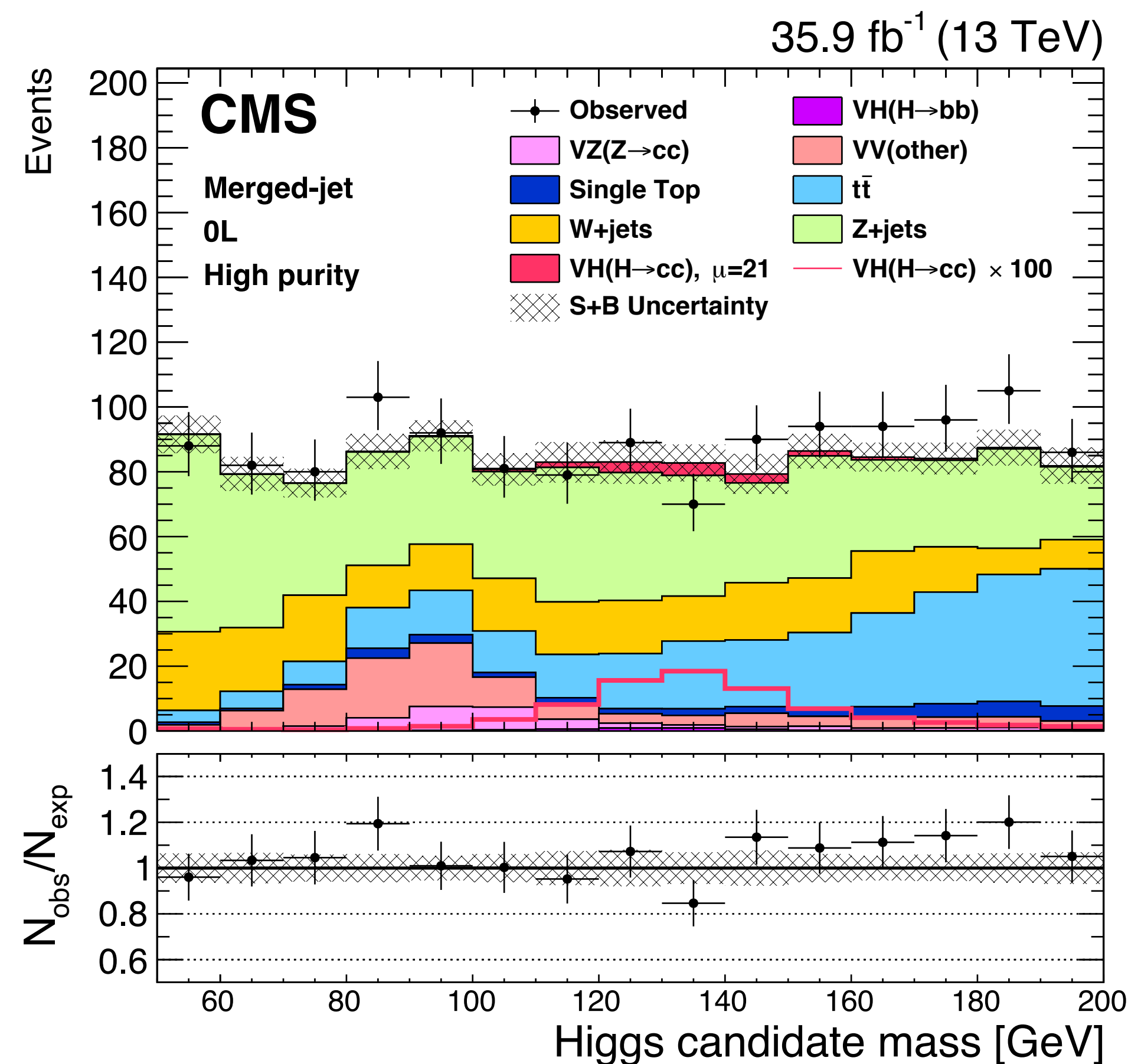
Deep double-b



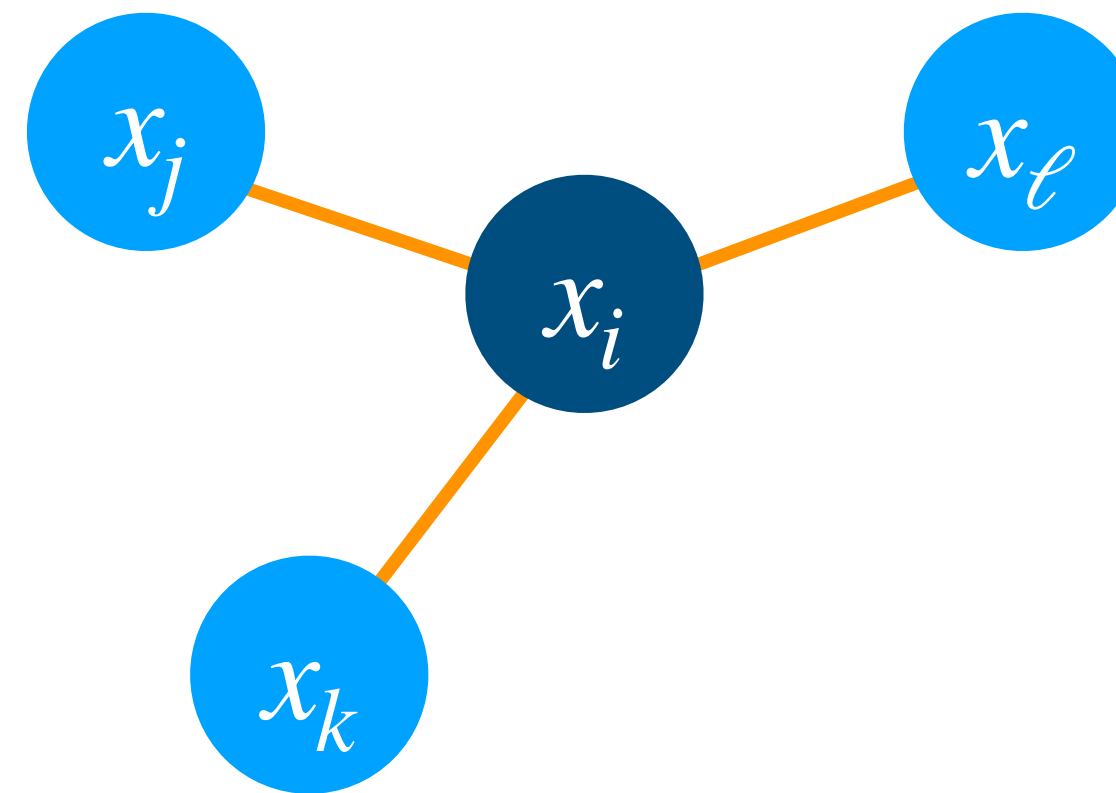
Deep AK8



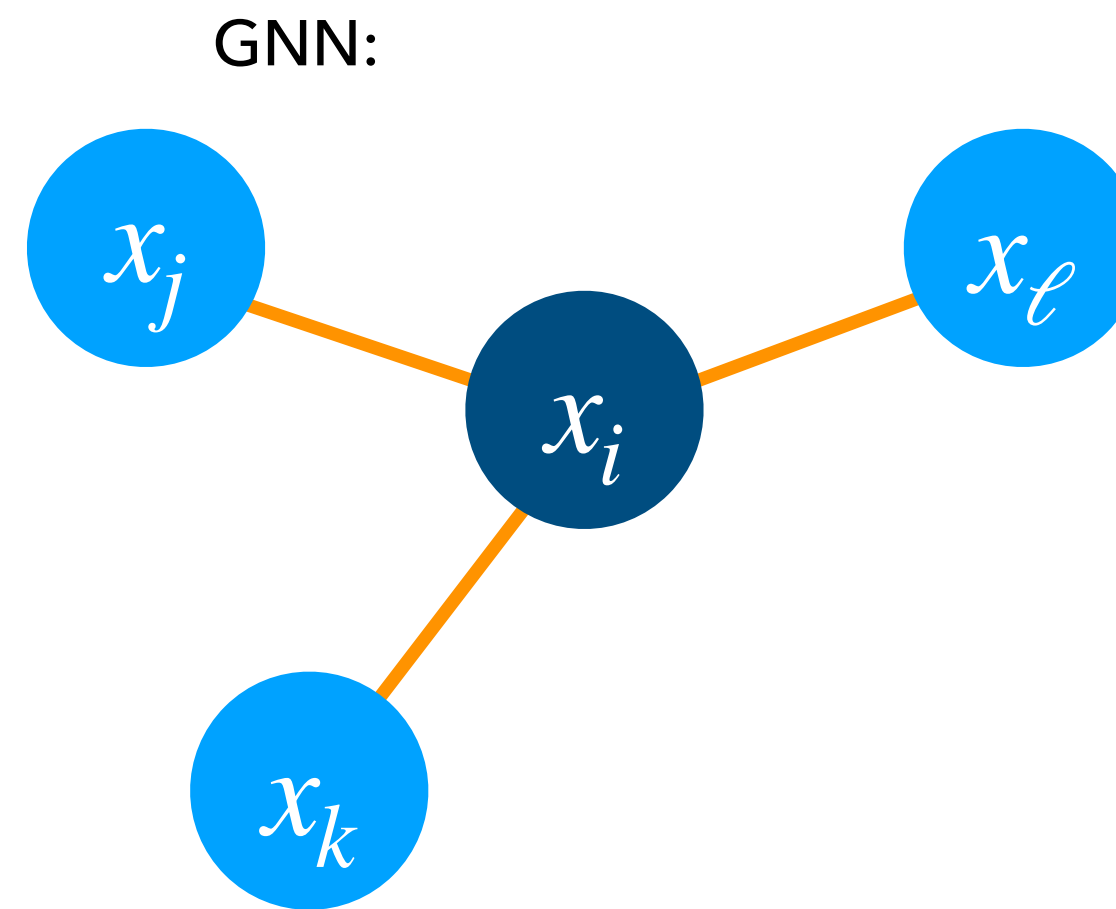
- ▶ New tagging (deep AK8 and deep double-b) methods used in CMS VH(cc) and ggH(bb) searches
- ▶ These searches made possible because of these methods!



GNN:

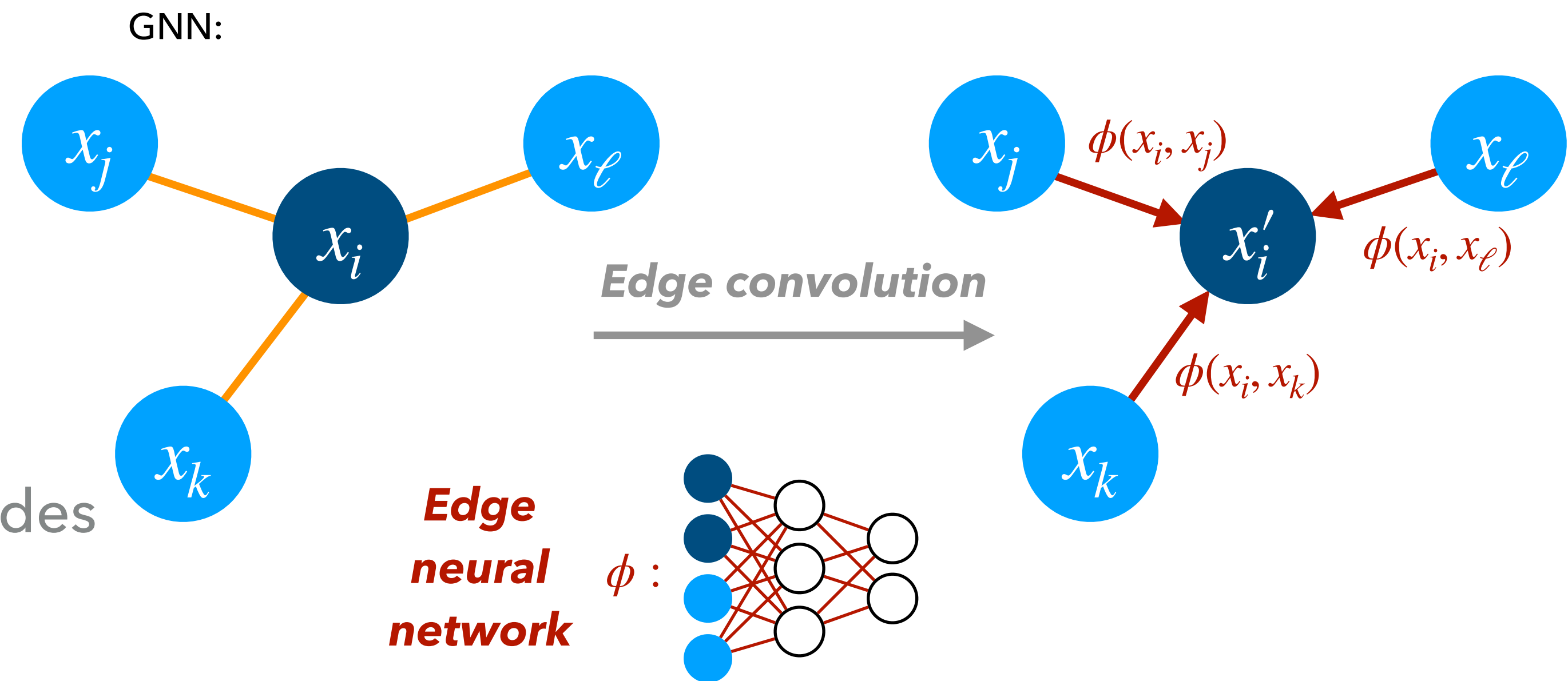


- ▶ Graph neural networks for jet tagging:
  - ▶ Each jet is treated as a graph of connected nodes (particles)

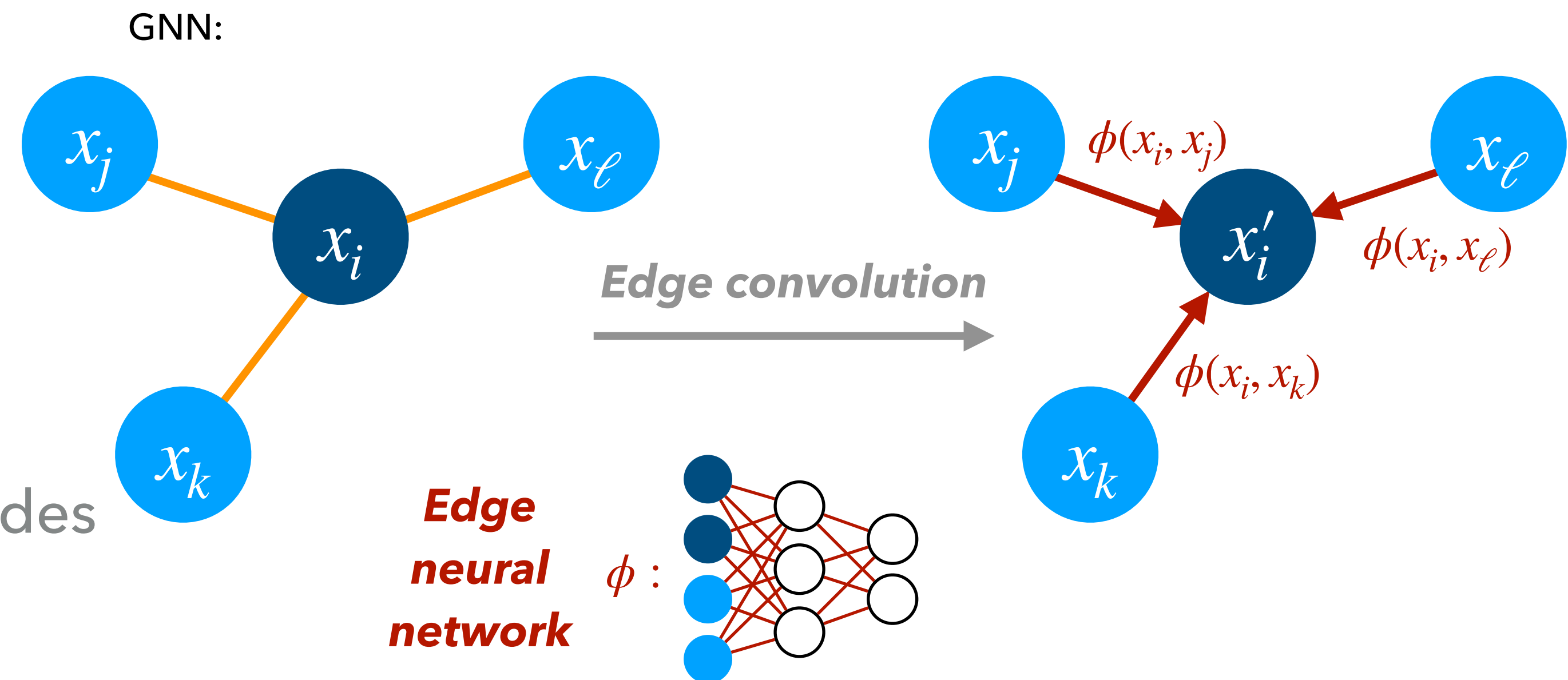


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  - ▶ Graph-level outputs are obtained by summing over node-level features



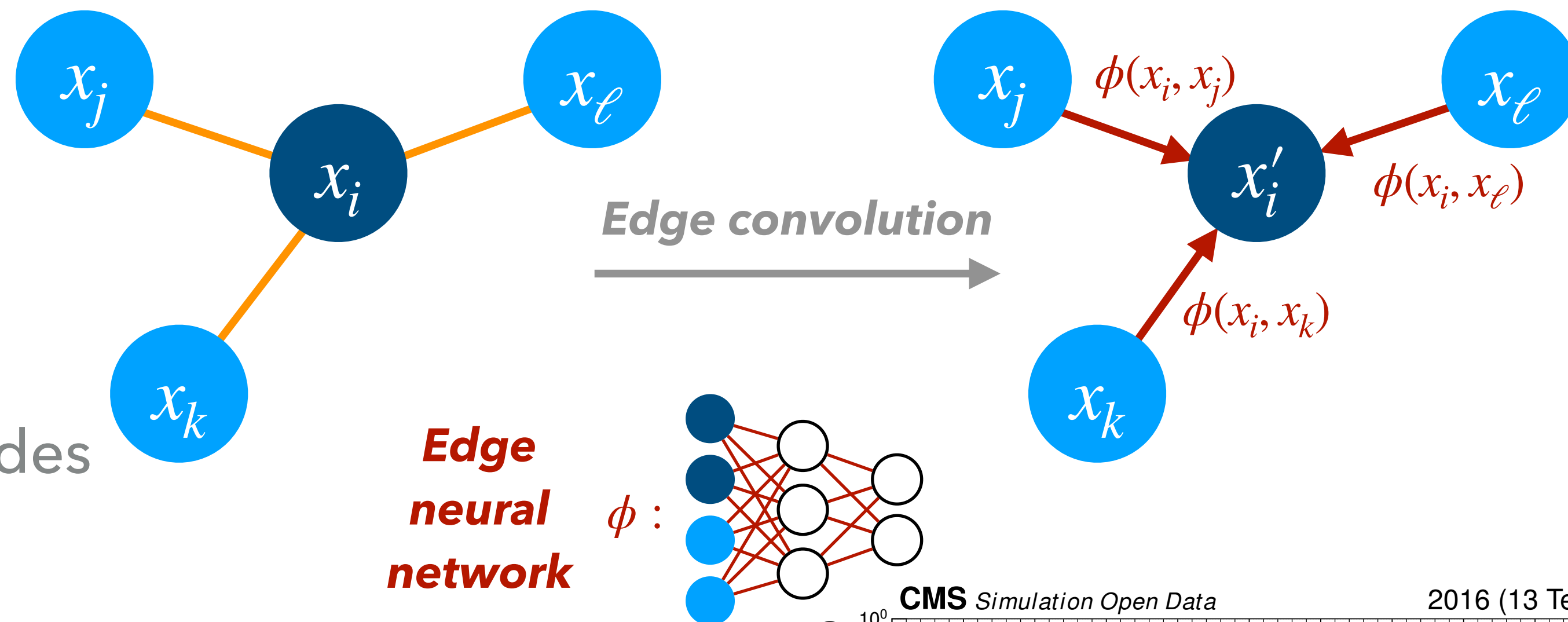
## Graph neural networks for jet tagging:

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- NN learns to update node features from relationships between pairs of nodes
- Graph-level outputs are obtained by summing over node-level features

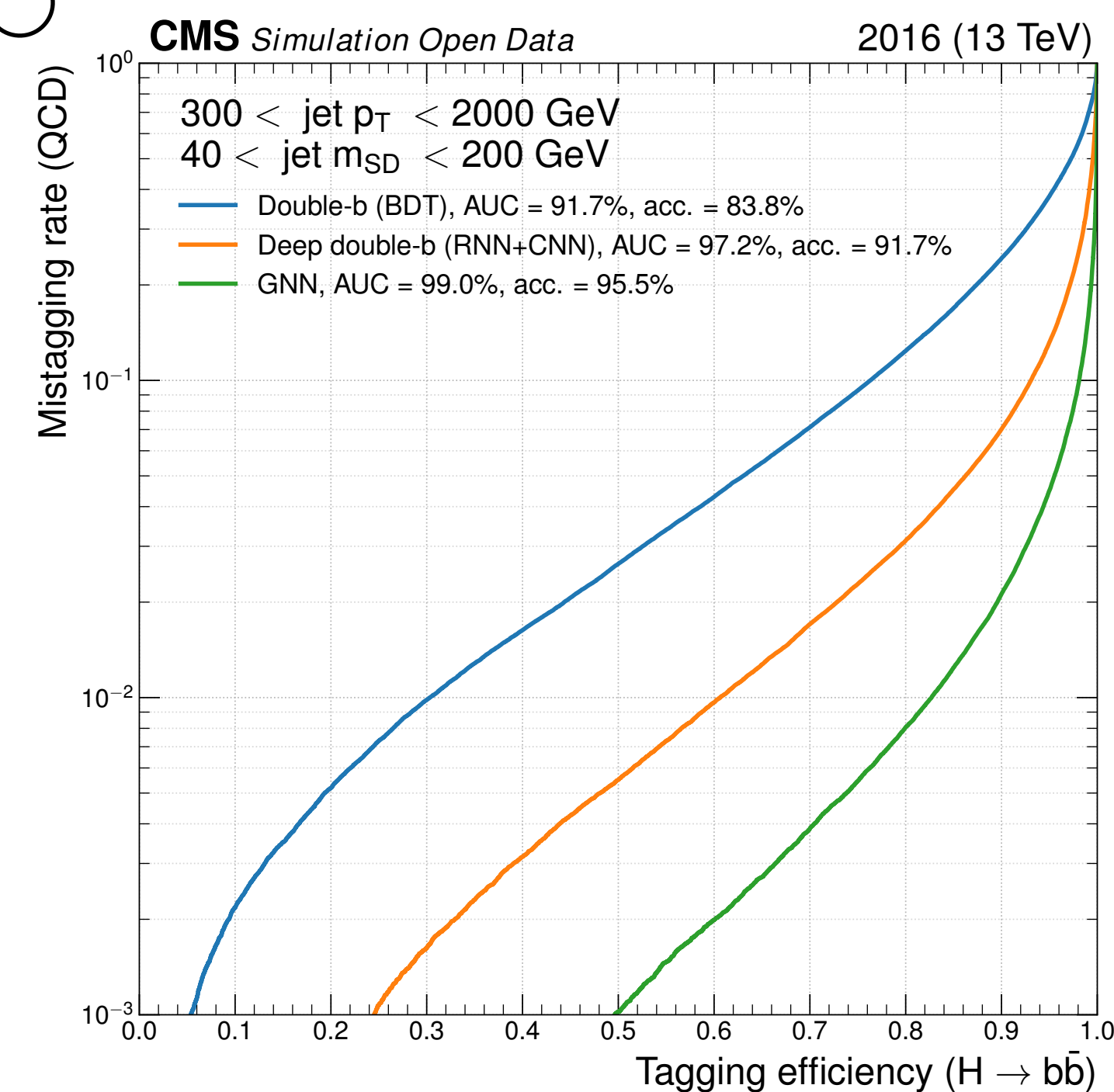
## Examples:

- ParticleNet [[arXiv:1902.08570](https://arxiv.org/abs/1902.08570)], based on DGCNN [[arXiv:1801.07829](https://arxiv.org/abs/1801.07829)]
- JEDI-Net/HiggsInteractionNet [[arXiv:1908.05318](https://arxiv.org/abs/1908.05318), [arXiv:1909.12285](https://arxiv.org/abs/1909.12285)], based on IN [[arXiv:1612.00222](https://arxiv.org/abs/1612.00222), [arXiv:1806.01261](https://arxiv.org/abs/1806.01261)]
- ABCNet [[arXiv:2001.05311](https://arxiv.org/abs/2001.05311)], see [talk by Vinicius](#)
- Energy Flow Networks [[arXiv:1810.05165](https://arxiv.org/abs/1810.05165)]

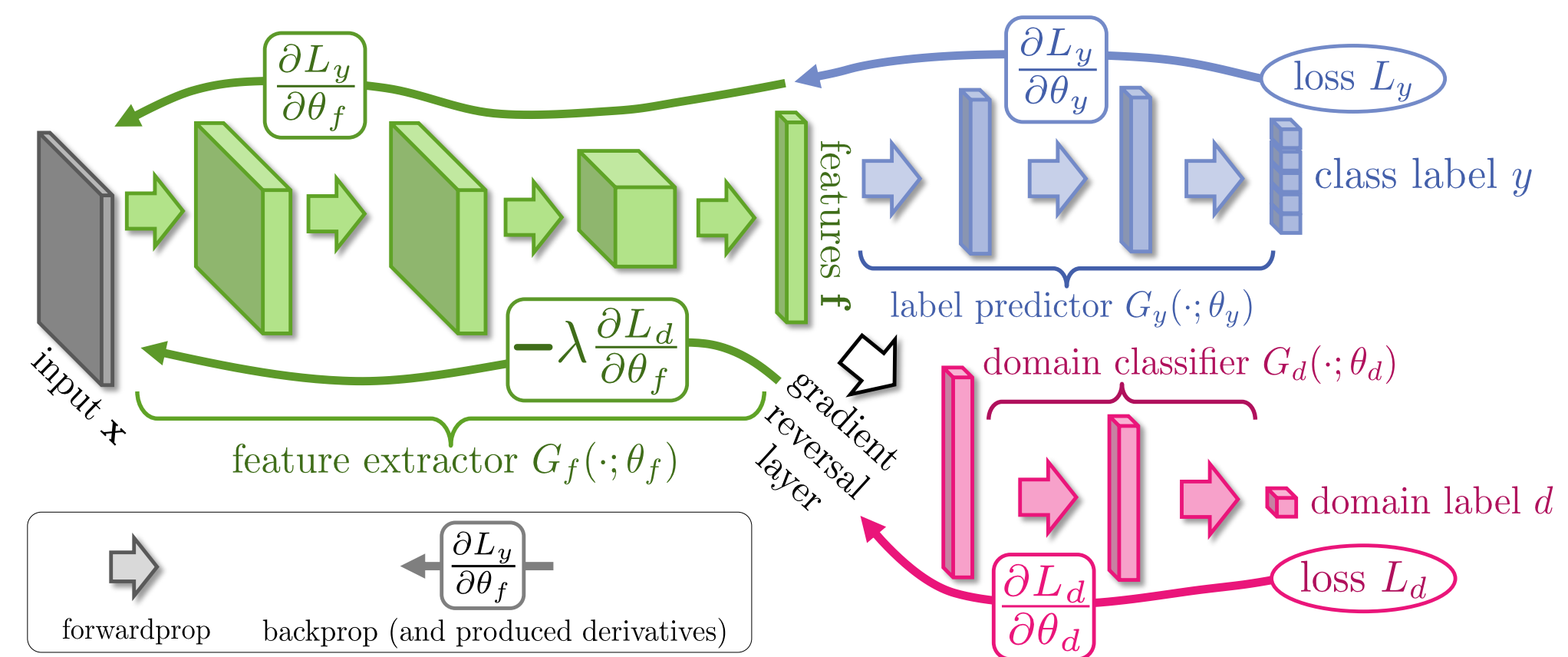
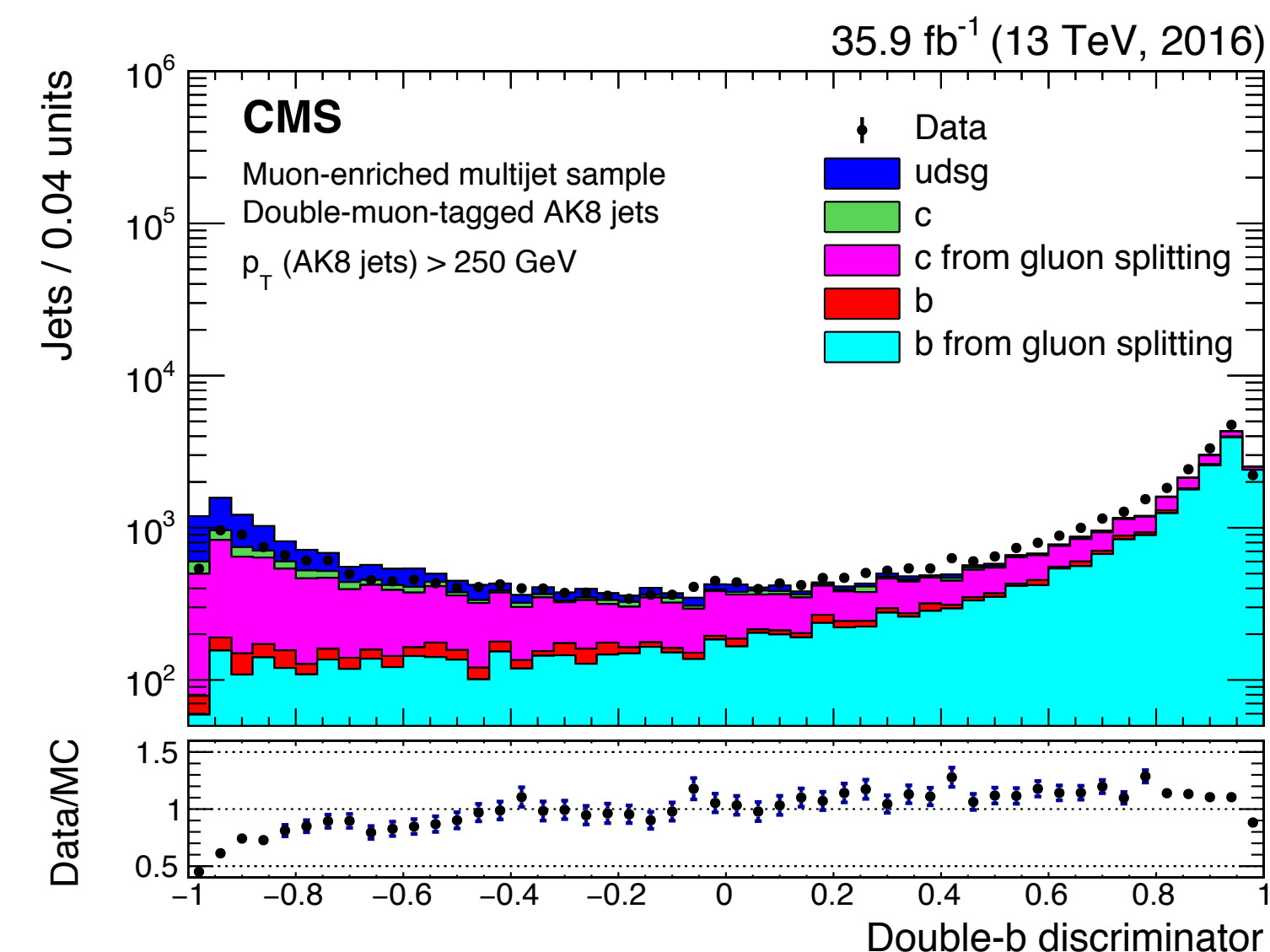
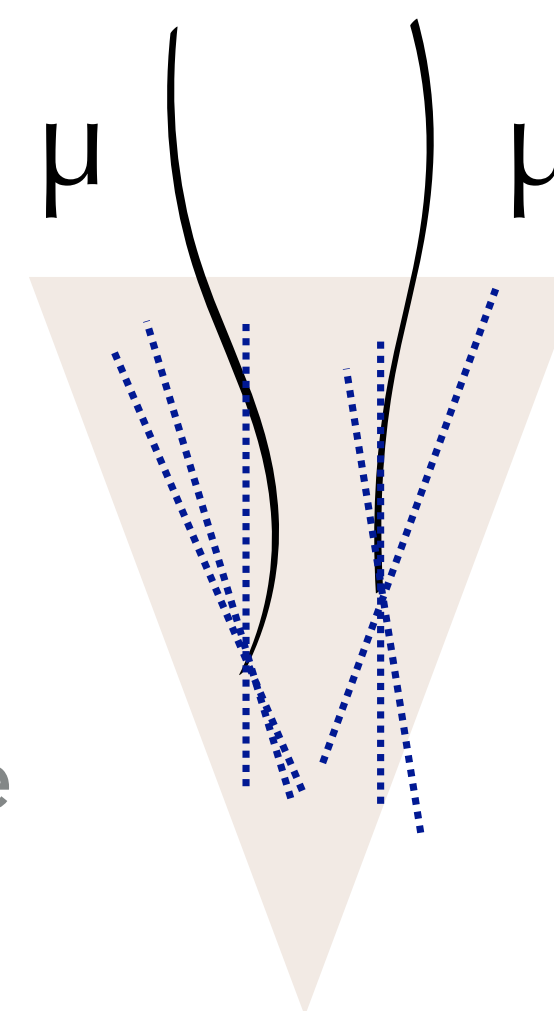
GNN:



>80% H(bb)  
efficiency for  
1% mis-id



- ▶ Data/simulation correction scale factors
  - ▶ Often measured using “proxy” processes like  $g \rightarrow bb$ 
    - ▶ Difficult if tagger can tell  $g \rightarrow bb$  and  $H \rightarrow bb$  apart
    - ▶ Using  $Z \rightarrow bb$  is starting to become common
  - ▶ What about  $cc$ ?
    - ▶ Same concepts, but smaller rates make measurement more difficult
  - ▶ Use ML to minimize data/simulation differences  
[[arXiv:1912.12238](#)]
- ▶ Estimate uncertainties/resolution directly [[arXiv:1912.06046](#)]
- ▶ Decorrelation with analysis variables
  - ▶ Often want to prevent algorithm from learning aspects unconnected from the flavor element that you may use in the analysis (e.g.  $p_T$ , mass, etc.)
  - ▶ Solutions explored so far: adversarial neural networks [[arXiv:1611.01046](#), [arXiv:1409.7495](#)], “brute force” designed decorrelated taggers (DDT) [[arXiv:1603.00027](#)], loss function penalty, training samples with varying mass and  $p_T$



# FLAVOR TAGGING IN THE TRIGGER

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## ► High-level trigger

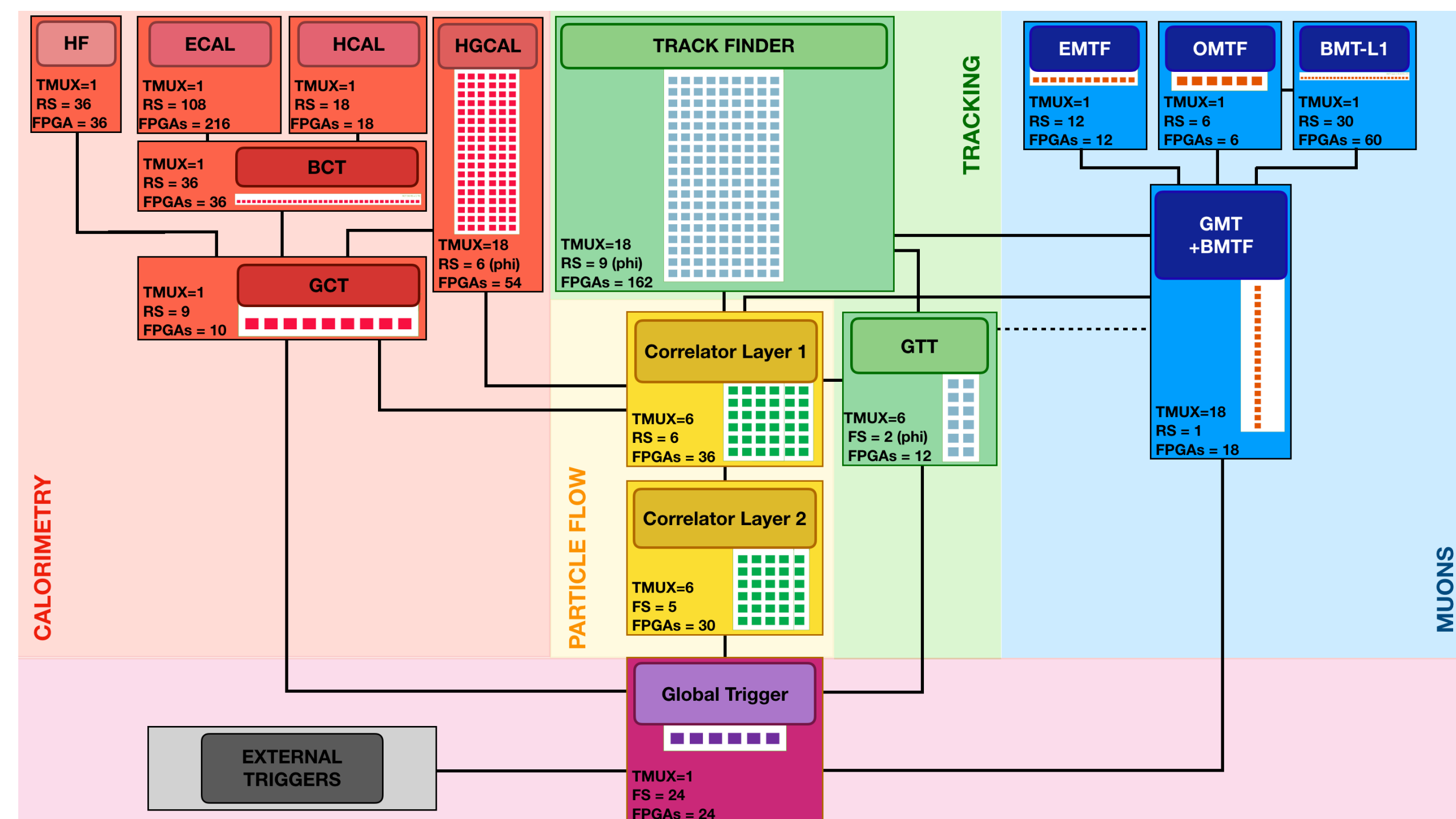
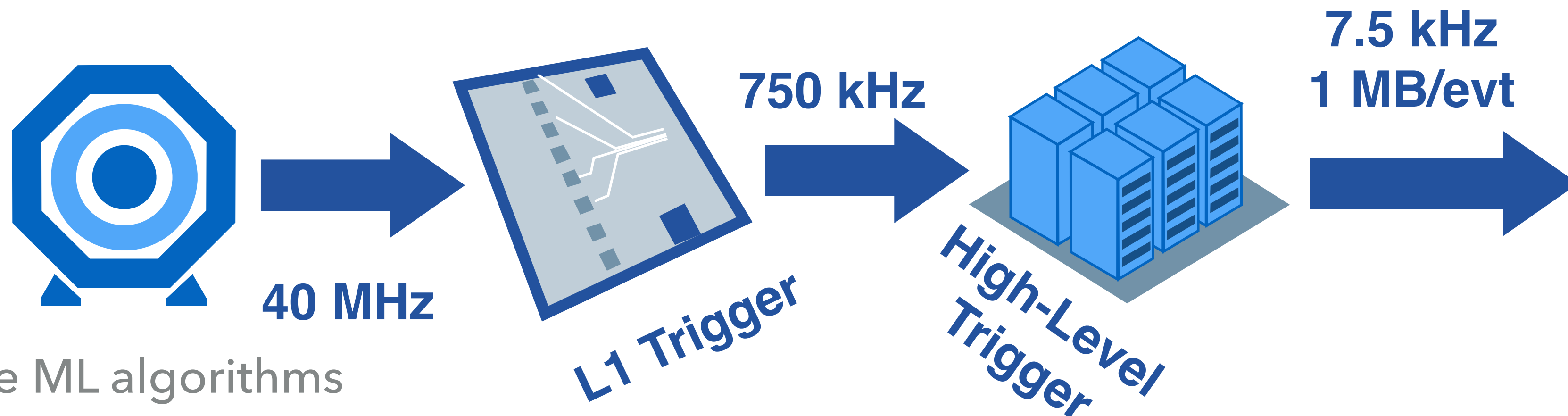
- b-tagging algorithms available using re-optimized tracking and fast primary vertex finding

- May need ways to speed up large ML algorithms (dedicated re-training may improve perf. as well)

- Using GPUs can help (e.g. Allen in LHCb, Patatrack [[arXiv:2008.13461](https://arxiv.org/abs/2008.13461)] and SONIC in CMS [[arXiv:2007.10359](https://arxiv.org/abs/2007.10359)])

## ► Level-1 trigger

- ML algorithms in FPGA firmware may be enabled with tools like [hls4ml](https://arxiv.org/abs/1804.06913) [[arXiv:1804.06913](https://arxiv.org/abs/1804.06913)]
- In CMS only outer tracker will be available



- ▶ Heavy flavor tagging is a crucial tool for Higgs physics
- ▶ Methods have improved dramatically in recent years (and may continue to improve a bit)
  - ▶ At the same time, new issues (analysis-related, experimental, and computational) to consider
- ▶ Outlook is bright



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**BACKUP**